Assessment of Nitrogen and Phosphorus Control Trade-Offs Using a Water Quality Model with a Response Surface Method

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Abstract: Excessive nutrient loads to the Chesapeake Bay cause violations of the new dissolved oxygen water quality standard established to protect the Bay's living resources. Reducing nitrogen and phosphorus loads is necessary to achieve the dissolved oxygen standard. Based on a set of water quality model runs, a response surface method to establish a function of dissolved oxygen (DO) versus total nitrogen (TN) and total phosphorus (TP) loads was used, which plots as a three-dimensional surface. For a specific criterion for DO, i.e., achievement of the DO standard, a curve of DO versus TN and TP loads that meets the DO criterion can be isolated. Each of the paired TN and TP loads on this trade-off curve results in an equivalent level of DO, but usually at different nutrient reduction costs. This paper explores cost-effective alternatives in nutrient reduction to achieve the DO water quality standard in the deep water designated use of Segment CB4, which is the last and most difficult region for achievement of DO standards in the Chesapeake. This paper analyzes DO response surface plots and nitrogen–phosphorus trade-off curves. The effects of nutrient limitation on algal growth, water clarity, and DO concentrations in two different nitrogen and phosphorus load scenarios are examined to understand the responses of water quality to nitrogen and phosphorus trades.

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Introduction

The Chesapeake Bay (hereafter referred to as the Bay) is one of the largest and most biologically productive estuaries in the world. In the latter part of the 20th century, degradation of water quality due to excessive nutrient inputs from the 166,000 km^2 watershed resulted in increasing volumes of hypoxic and anoxic waters (Adelson et al. 2001; Kemp et al. 2005). The Chesapeake 2000 agreement (CEC 2000) set a goal of achieving dissolved oxygen (DO) and other water quality standards to remove the Bay from the list of impaired waters by 2010. Throughout the history of the Chesapeake Bay Program partnership (www.chesapeakebay.net), there have been numerous analyses of the influence of nitrogen (N) and phosphorus (P) loads on Bay hypoxia and anoxia (Gillelan et al. 1983; Thomann et al. 1994; Boynton et al. 1995; Kemp et al. 2005). Early on, the important role that both nitrogen and phosphorus play in controlling algal production and subsequent low DO conditions in tidally influenced waters was firmly established (Gillelan et al. 1983; D'Elia et al. 1992). During the development of nutrient allocations in 1992, the importance of controlling both nitrogen and phosphorus loads was reaffirmed (Boynton et al. 1995), as it was again in the 2003 development of nitrogen, phosphorus, and sediment allocation caps (CBPO 2003). Controlling both nitrogen and phosphorus loads is necessary due to spatial and temporal variations in nitrogen versus phosphorus limitation in the Chesapeake.

The relative importance of nitrogen versus phosphorus loads on water quality and the trade-offs between relative amounts of nitrogen–phosphorus control have been suggested (Thomann et al. 1994), and the Chesapeake Bay Estuarine Model (Cerco and Meyers 2003; Cerco and Noel 2004) has been used to specifically address the problem of anoxia. However, a model scenario provides insight to only a specific loading condition. In order to find nutrient loads that correlate to a specific response requirement many trial scenarios are required. In a complex system, like the Chesapeake Bay, there is no simple equation to relate DO with nutrient loads. After all, more than 80 governing partial differential equations are involved in the water quality model. However, a response surface (Thomann et al. 1994; Khuri and Cornell 1996), based on a set of a few model scenarios, can provide an analytic expression of water quality response as a function of independent variables, such as nutrient loads. Wang et al. (2002, 2006) used the response surface method to analyze the response of Chesapeake Bay's ecosystem to nutrient and sediment loads, indicating that the same level of water quality can be achieved by different combinations of nitrogen, phosphorus, and sediment reductions. In this paper, the writers further apply the response surface method to analyze nitrogen–phosphorus trade-offs for development of cost-effective load reductions to achieve the DO water quality goal. This provides flexibility in water quality management in planning and implementing cost-effective point source and nonpoint source controls.

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Method

Based on a set of water quality model results, a response surface method was used to establish a function of DO as the dependent variable and total nitrogen (TN) and total phosphorus (TP) loads as independent variables, e.g., DO=f (TN, TP). For a specific DO criterion, a set of TN and TP trade-off loads can be determined (Wang et al. 2006). The DO problem in the Chesapeake Bay is due to excessive algal growth and subsequent decay of algal biomass in bottom waters below the pycnocline. Although algal growth requires dissolved inorganic nitrogen (DIN) and dissolved inorganic phosphorus (DIP), the Chesapeake Bay Program has long determined that controls of TN and TP loads from the watershed are needed due to the long residence time of nitrogen and phosphorus loads in the estuary and multiple opportunities for conversion among organic and inorganic nutrients (Thomann et al. 1994; Koroncai et al. 2003). Therefore, TN and TP loads are selected as the explanatory variables in the response surface in this paper.

The year 2002 version (i.e., with 12,920 model cells) of the Chesapeake Bay Estuarine Model (Cerco and Noel 2004) was used. The model was fully calibrated. The average mean errors (i.e., the mean of the differences between model prediction and field observation) of the simulated chlorophyll concentration, bottom DO, and light attenuation in the main stem Bay are -0.53 μg/L, +0.32 mg/L, and +0.02/m, respectively. The absolute mean errors for them are 5.01 μg/L, 1.47 mg/L, and 0.36/m, respectively.

Nine model scenarios were selected to elucidate the response surface decision space. The 2000 Progress Scenario (PR2000) is the reference condition used and has relatively high levels of nutrient loads compared to the future nutrient reductions that are planned to remove water quality impairments. The PR2000 uses input loads associated with year 2000 land use, populations, nutrient applications, point source loads, and management conditions, and runs for a 10-year simulation period covering the 1985–1994 hydrology. This scenario represents the Bay's responses, under average hydrological conditions, to the year 2000 management conditions (Koroncai et al. 2003). In this scenario the TN and TP loads from the watershed were 129.3 and 8.664 kt/year, respectively. The other eight scenarios have varying 0, 30, and 60% reductions from the PR2000 reference in nitrogen and phosphorus loads. Each scenario was run for 10 years using the 1985–1994 hydrology, using a 5 min time step and daily outputs. The averaged annual, seasonal, or monthly values as required in this study were used.

Based on the previous study (Wang et al. 2006) the aforementioned nine model scenarios were selected and used a linear regression method was used to establish a quadratic polynomial equation of DO as a function of TN and TP loads. The least-squares method was applied to derive regression coefficients.

This paper focuses on the attainability of DO criteria in key designated use areas of the Bay (USEPA 2003) versus total nitrogen and total phosphorus loads to the Bay. The DO criteria in deep water of Segment CB4 (CB4-DW) is most difficult to achieve. Segment CB4 is in the center of a large anoxic\hypoxic region of the Bay, and is the region of focus for nutrient reduction for basins of the upper and middle Bay. The writers examine how reductions of nitrogen and phosphorus loads cause reductions of algae and improvements in DO and water clarity. Algal limitation from nitrogen, phosphorus, or light, which reflect the effectiveness of nutrient reduction, are also examined.

The model simulates three types of algae, diatoms, green algae, and blue-green algae, and converts these state variables to chlorophyll concentrations for comparison with observed concentrations during model calibration. The following discussion is based on surface chlorophyll concentrations.

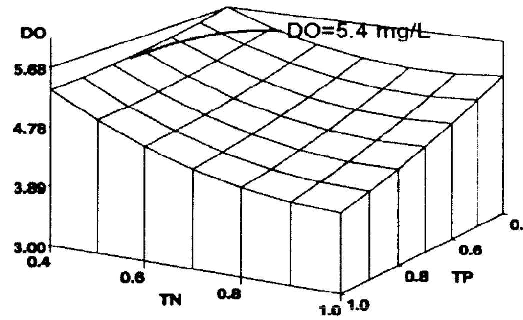

Fig. 1. Response of summer average DO in CB4-DW to TN-TP loads to the Bay; TN and TP axes are loads as fraction of the PR2000 Scenario loads

Nitrogen and Phosphorus Load Control for DO Attainment in CB4-DW

Dissolved Oxygen Response Surface and Its Attainment Curve for N–P Equivalence

The writers used the response surface method to establish a quadratic function of average summer DO in CB4-DW versus TN and TP loads to the Bay

$$DO = a\mathrm{TN}^2 + b\mathrm{TP}^2 + c\mathrm{TNTP} + d\mathrm{TN} + e\mathrm{TP} + f \qquad (1)$$

where, a–f=coefficients derived from regression; a=3.127; b =0.7923; c=−1.743; d=−4.583; e=−0.9773; f=7.553. DO is in milligrams per liter; the TN and TP loads are expressed as a fraction of PR2000 conditions. The R^2=0.99 and the root mean square error=0.001 mg/L. Eq. (1) can be plotted graphically as a three-dimensional surface of DO versus TN and TP loads (Fig. 1).

The CB4-DW consists of more than 100 model cells. A strict application of the DO criterion (USEPA 2003) for a deep-water designated use area would apply limits of DO equal to or greater than 3 mg/L at all times in the criteria months of June, July, August, and September and for all the individual cells. Dissolved oxygen less than 3 mg/L would be a violation of this strict criteria. The criteria violation of a designated use area is calculated by the ratio of the cumulative volume for the cells in the months with violations divided by the total cumulative volume for all cells in the designated use area in all criteria months over the 10 years of the simulation period. To ensure all cells in CB4-DW have DO no less than 3 mg/L (i.e., zero violation of any time or space), the summer average DO in CB4-DW is higher than 3 mg/L. Still using the set of nine model outputs, the writers applied a linear regression method to get a relationship between violation (V) and summer average DO in CB4-DW

$$DO = y(V) = -131.5V^3 + 39.75V^2 - 11.80V + 5.403$$

Denoting DO_0 as the summer average DO when V approaches to zero, one has

$$DO_0 = \lim y(V) = 5.4 \text{ mg/L}$$

$$V -> +0$$

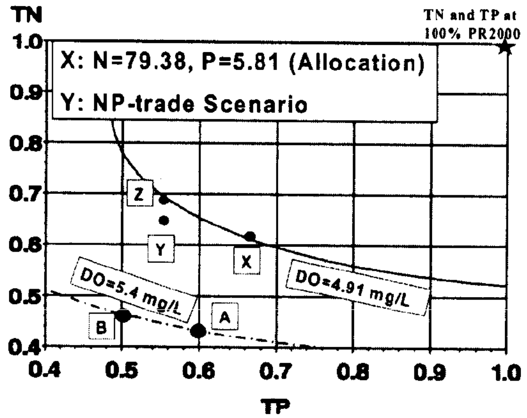

Fig. 2. Contours of DO curve versus N–P loads for CB4-DW; TN and TP axes are loads as fraction of the PR2000 scenario loads

It yields $DO_0=5.4$ mg/L, which is the minimum summer average DO in CB4-DW which would ensure that all 100 cells of CB4-DW have DO$\geq$3 mg/L at all times.

Using a plane of DO=5.4 mg/L to cut the surface of Fig. 1 yields a curve, called the DO=5.4 mg/L trade-off curve. The equation of this trade-off curve can be derived by substituting 5.4 for DO in Eq. (1): $a\,\mathrm{TN}^2+b\,\mathrm{TP}^2+c\,\mathrm{TN}\,\mathrm{TP}+d\,\mathrm{TN}+e\,\mathrm{TP}+g=0$, where $g=f-5.4$.

The equation of the curve can be rearranged as TN in terms of TP

$$\mathrm{TN}=\{-(d+c\mathrm{TP})-[(d+c\mathrm{TP})^2-4a(b\mathrm{TP}^2+e\mathrm{TP}+g)]^{1/2}\}/2a \tag{2}$$

On this curve, the summer average DO of the designated use area equals 5.4 mg/L. The dashed curve in Fig. 2 is a plane view of the DO=5.4 mg/L tradeoff curve for TN and TP loads. The TN and TP loads at any point of this curve would just meet the strict DO criteria. For example, a reduction of 56.7% TN and 40% TP (at Point A), i.e., total nitrogen and phosphorus loads at 43.3 and 60% of the 2000 Progress Scenario loads, would achieve the strict DO criteria as would Point B with less reduction of TN (46.6% of the PR2000 loads) and more reduction of TP (50% of the PR2000 loads). Any pairs of TN–TP loads on this trade-off curve will yield approximately equal DO responses.

TN–TP Trade-Off Rates

From the curve of Eq. (2), if TP is specified, then TN can be defined accordingly. The trade-off rate, $d\mathrm{TN}/d\mathrm{TP}$, at any point can be obtained by the derivative of Eq. (2)

$$d\mathrm{TN}/d\mathrm{TP}=\{-c-0.5[(d+c\mathrm{TP})^2-4a(b\mathrm{TP}^2+e\mathrm{TP}+g)]^{-1/2}\;2c(d+c\mathrm{TP})-4a(2b\mathrm{TP}+e)\}/2a$$

or it can be estimated from Fig. 2.

The N–P trade-off rates vary along the curve (Fig. 2). For example, at Point A, $d\mathrm{TN}/d\mathrm{TP}=-0.268$. The instantaneous TN:TP trade-off rate is $-26.8:100$ using the metric of a percent TN or TP reduction from the PR 2000. Using the metric of mass with units of kilotons/year and the mass loads of TN=129.3 and TP=8.664 kt/year in the PR2000, the TN:TP mass trade-off rate is -129.3×26.8 to 8.664×100, or 4.00 to -1. A decrement of one mass unit of TP with an increment of 4.0 mass units of TN is estimated to achieve the same DO response in the critical region of CB4-DW at Point A on the trade-off curve.

If the change of one loading constituent (e.g., TP) is specified over a segment of the trade-off curve, for example, $d\mathrm{TP}=-0.1$ from 0.6 (Point A) to 0.5 (Point B) of PR2000, the average trade-off rate can be estimated from the curve of DO=5.4 mg/L in Fig. 2, yielding $d\mathrm{TN}:d\mathrm{TP}=0.033:-0.1$. Referring to units of mass, the TN:TP trade-off is 4.92 to -1. In other words, an average estimated increase of 4.92 kt/year of nitrogen is offset by an additional 1.0 kt/year decrease in phosphorus to yield the same DO response over the curve from A to B in Fig. 2.

Exploration of TN–TP Trade Allocations

Allocation Scenario

The preceding section discussed load reductions and the nitrogen and phosphorus trade-offs for an absolute and unequivocal attainment of DO not less than 3.0 mg/L at any time or place in CB4-DW. This requires high nitrogen and phosphorus load reductions to reach a summer average DO of 5.4 mg/L. This strict imposition of nonviolation at any time or in any space of the 3.0 mg/L DO minimum in CB4-DW is unnecessary for the protection of living resources and for achieving the water quality standards based on USEPA guidelines allow about a 10% exceedance of the DO criteria in time and space (Koroncai et al. 2003). The 10% allowable exceedance corresponds to an independent assessment by the Bay Program that an approximately equivalent level of occasional time and space incursions of DO less than 3.0 mg/L are ecologically unharmful to the key biological communities protected by the DO standard.

The Bay Program has caps on nitrogen and phosphorus loads to the Bay that achieve the DO water quality standard with loads of 79.38 and 5.81 kt/year for TN and TP, respectively (Koroncai et al. 2003). This corresponds to TN=61.4% and TP=67% of the Progress 2000 Scenario loads as shown by Point X in Fig. 2. The cap loads are allocated to nine major river basins. The corresponding scenario is called the allocation scenario, with an estimated summer average DO concentration of 4.91 mg/L and a level of 7% time and space incursions of DO$<$3.0 mg/L in CB4-DW. The following explores alternative nitrogen and phosphorus reductions to achieve similar DO conditions as in the allocation scenario in CB4-DW.

NP-Trade Scenario

Municipal wastewater treatment plants contribute significant nitrogen and phosphorus loads to the Chesapeake and influence CB4 water quality. In some cases, operational costs are less for reducing phosphorus than for reducing nitrogen at wastewater treatment plants. Thus, the writers explore an alternative hypothetical nitrogen and phosphorus reduction allocation which would allow the five basins that have a significant influence on CB4-DW to have less nitrogen reduction but more reductions in phosphorus. The five basins having a significant influence on CB4-DW are the Susquehanna, Western Shore Maryland, Patuxent, Potomac, and Eastern Shore Virginia Basins (Wang et al. 2004). In these basins the hypothetical allocation would have a lower total phosphorus load but a higher total nitrogen load than the allocation scenario. If the paired loads remain on the trade-off curve, then CB4-DW should still meet the same water quality as in the allocation scenario, although this would need to be ultimately confirmed by a verification scenario. Any point of the DO=4.91 mg/L trade-off curve in Fig. 2 would be a potential candidate for this hypothetical trade-off.

For example, at Point Z, the TP load is 55.5% and the TN load is 69% of the PR2000 load. Considering errors in the model and the response surface, and to avoid trade-offs causing possible adverse effects on water quality attainment in other designated use areas, the proposed TN load could be conservatively set to 65% of PR2000 (Point Y). The TN and TP loads at Point Y are 84.05 and 4.81 kt/year, respectively. This NP-trade scenario decreases the TP load by 1.00 kt/year, but increases the TN load by 4.67 kt/year from the allocation scenario.

The hypothetical trade-off allows an additional 1.00 kt/year of TP from the Susquehanna, Western Shore Maryland, Patuxent, Potomac, and Eastern Shore Virginia Basins to be traded for 4.67 kt/year of nitrogen load increase. The NP-trade scenario yields average summer DO in CB4-DW at 4.95 mg/L, a slight improvement over the initial target of the allocation scenario. Such a hypothetical trade-off may reduce the overall cost of compliance with the water quality standard. The next section discusses the mechanisms and nutrient dynamics of TN–TP trade-off on water quality attainment.

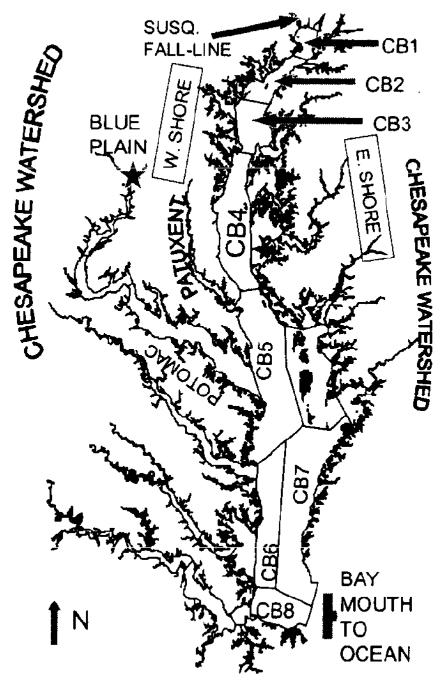

Fig. 3. Chesapeake Bay main stem and the tidal portion of its major tributaries

Discussion

Basis of Nutrient Equivalence for TN–TP Trading

The nutrient reduction for DO improvement is mainly through the reduction of algal biomass. Algal growth requires light and nutrients, such as DIN, DIP, and silica (for diatoms). Algal production also increases as a function of light intensity until an optimal intensity is reached (Cerco 1995). Based on the writers' study, in 99% of the cases, silica is not a limiting factor for algae in the Chesapeake and is, therefore, excluded from the discussion.

The Chesapeake Bay Estuarine Model uses the Michaelis–Menten saturation kinetics to simulate nutrient-dependent algal growth. Applying the principal of Liebig's "law of the minimum" (Odum 1971), growth is determined by the nutrient in the least supply

$$\text{minimum}\,[\text{DIN}/(K_{\text{DIN}}+\text{DIN}),\text{DIP}/(K_{\text{DIP}}+\text{DIP})]$$

where K_{DIN} and K_{DIP}=half-saturation constants for DIN and DIP uptake by algae. The K_{DIN} and K_{DIP} for total phytoplankton have a range in the literature of 0.001–0.4 g(N)m^{-3}, and 0.0005–0.03 g(P)m^{-3} (USEPA 1985). The half-saturation constants are set at 0.02 g(N)m^{-3} and 0.0025 g(P)m^{-3}, respectively, in the model (Cerco and Noel 2004).

If the system is originally phosphorus limited, a further decrease in DIP intensifies the phosphorus limitation. Therefore, the system can receive a higher nitrogen load with the decrease of phosphorus load, and still yield a similar level of algal biomass and DO as the original system.

Based on modeled daily DIN, DIP, and light intensity in Bay segments (Fig. 3), it was determined which was to be the dominant factor limiting algal growth on any day. The writers then calculated relative frequencies of daily limitations among DIN, DIP, and light in the spring (March–May) and summer (June–August) seasons (Figs. 4 and 5). In the allocation scenario, phosphorus limitation is frequent in the upper and mid-Bay, including CB1, CB2, CB3, and CB4, particularly in the spring (Fig. 4). With the hypothetical TN–TP trade (Fig. 5), reduced TP loads cause increased phosphorus limitation compared to the allocation scenario and nitrogen limitation is reduced with the increase of TN load. Both scenarios were simulated with the same amount of sediment loads. The decrease of light limitation by the TN–TP trade is in part due to the increased frequency of phosphorus limitation but also reflects in part a reduction of algal production, particularly in the tidal fresh and oligohaline upper Bay due to increasing overall nutrient limitation (Fig. 6). Consequently, water clarity improves, the light extinction coefficient (K_e) decreases (Fig. 7), and summer bottom DO increases very slightly in the upper Bay (Fig. 8). These plots indicate that the TN–TP load trade (Point Y of Fig. 2) slightly improves water quality in the upper Bay. The following section further discusses nitrogen versus phosphorus limitation both geographically and seasonally.

Geographical Variation of Nitrogen and Phosphorus Limitations

Acceptance of a TN–TP trade should be based not only on nondegradation or improvement in key regions such as CB4-DW, but also on the condition that no significant degradation of water quality occurs in other designated use areas.

The geographical variation in nitrogen and phosphorus limitation in the Chesapeake is primarily due to the nitrogen and phosphorus composition of the loading sources. Monitoring and research indicates that phosphorus is more limiting in the upper Bay, and nitrogen is more limiting in the lower Bay (D'Elia et al. 1986; 1992; Cerco 1995). At the head of tide (i.e., the fall-line) of the Susquehanna River in the upper Bay, mass loading of DIN to DIP is about 139:1 N:P. Algae take up nitrogen and phosphorus at a ratio of about 7:1 by mass (Redfield et al. 1966), and will deplete phosphorus before nitrogen in the upper Bay. The DIN/DIP ratio of the water entering from the ocean in the lower Bay is about 1.3:1. Algae in the lower Bay (e.g., CB7 and CB8), taking up nitrogen and phosphorus at the ratio of 7:1, will deplete nitrogen before phosphorus. Fig. 9 shows that the DIN/DIP ratio is

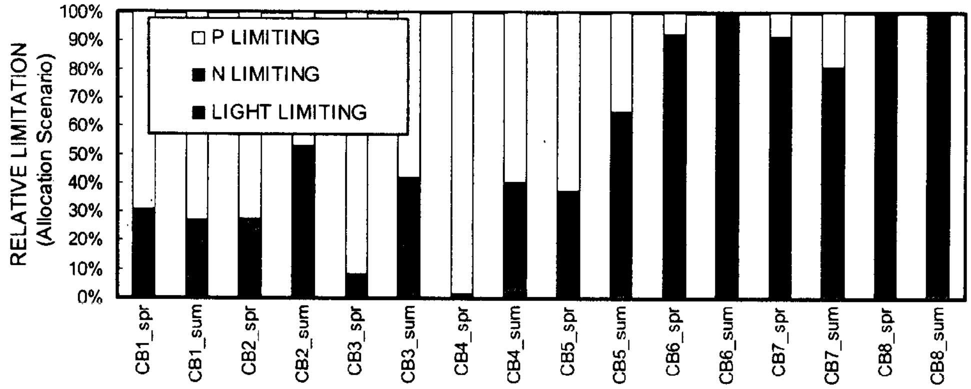

Fig. 4. N, P, and light limitations in surface water (allocation scenario) of eight main stem segments in spring ("spr") and summer ("sum")

greater than 7 in the upper Bay (CB1–CB4) in both the allocation and NP-trade scenarios. The latter scenario has a higher DIN/DIP ratio than the former, and intensifies P limitation in the upper Bay.

In contrast, the lower main stem Bay (CB5–CB8) has low DIN/DIP ratios, and is predominately nitrogen limited. The TN–TP trade with increasing total nitrogen loads can have an adverse effect. In both scenarios, in CB8, almost every day in the spring and summer nitrogen is limited (Figs. 4 and 5). Compared to the allocation scenario, after the TN–TP trade, the increased nitrogen loads by the N–P trade increase algae levels very slightly (Fig. 6). Consequently, DO in CB8 is slightly decreased in the spring, but the DO criteria are still fully achieved, as the DO criterion is already attained in CB8 even in the PR2000 Scenario (partly due to the influence of the ocean, which has much lower nutrient level than the upper Bay). Consequently, there is no adverse effect on the lower Bay's tidal tributaries.

Segments CB4 through CB6 are transitional between the two regions of the predominately phosphorus-limited upper Bay versus the predominately nitrogen-limited lower Bay. The number of days with phosphorus limitation increases slightly in this region after the TN–TP trade (Figs. 4 and 5). In this region, changes in bottom DO are insignificant, especially in the summer critical season (Fig. 8), and the DO concentration still achieves the criteria attainment with the NP-trade scenario.

The above-presented discussion indicates that although reducing both nitrogen and phosphorus from the PR2000 level is important to attain water quality standards in the Chesapeake Bay, there is flexibility in the relative nitrogen versus phosphorus reductions to achieve an equivalent water quality response.

Seasonal Variation of Nitrogen and Phosphorus Limitations

To examine whether a TN–TP trade-off is practical, one also needs to investigate flow and seasonal effects.

The annual peak of algal biomass occurs in the spring, driven by the high flows and nutrient loads of the spring freshet, the annual incremental spring thaw of snow and ice melt in the watershed resulting in higher spring flows (Harding et al. 2002). The runoff from the watershed brings high nutrient levels with high TN:TP ratios (usually greater than 50:1 of N:P) of nonpoint source loads to the Bay, playing an important role on the Bay's eutrophication. Organic material of the spring bloom subsequently provides organic substrate for the development of a robust microbial community whose metabolic activities delete oxygen and regenerate nutrients that support a summer algal community.

Bottom nutrient releases come from organic nitrogen and phosphorus that have been deposited over a period time. Boynton et al. (1995) estimated the annual mean pool sizes for nitrogen and phosphorus: 87% of the total nitrogen in the sediments, 12% in the water column, and <1% in the biota; stocks of total phosphorus are similarly distributed, but the sediment stocks are even more dominant. In the summer, low E_h values associated with

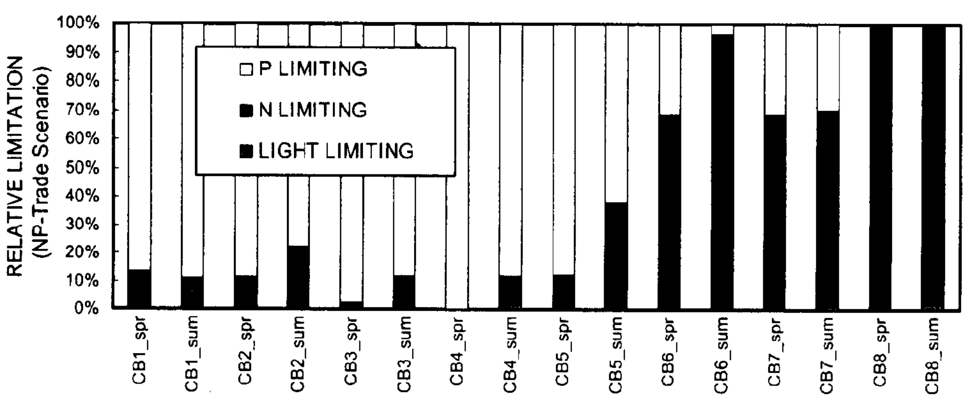

Fig. 5. N, P, and light limitations in surface water (NP-trade scenario) of eight main stem segments in spring ("spr") and summer ("sum")

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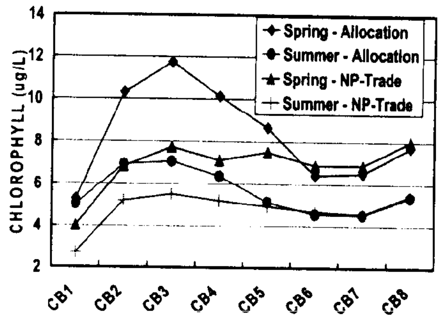

Fig. 6. Surface chlorophyll concentration in spring and summer for the allocation scenario and the NP-trade scenario

decay of the spring algae bloom in bottom sediments, promoting flux of phosphate and ammonia from the sediment to overlying waters. Compared to the spring freshet, the river discharge is reduced in the summer with lower DIN/DIP ratios which cause the Bay to have less phosphorus limitations in the summer than in the spring.

In the allocation scenario, in the upper and middle Bay's designated use areas, CB2–CB5, the spring has more phosphorus limitation than the summer (Fig. 4). The hypothetical N–P trade intensifies phosphorus limitation in both spring and summer (Fig. 5). The increase of phosphorus limitation from the allocation scenario to the NP-trade scenario is usually greater in the spring than in the summer. Consistently, the corresponding TN:TP ratios increase from the allocation scenario to the NP-trade scenario, with a greater increase in the spring than in the summer (Fig. 9). Consequently, the reduction of chlorophyll and improvement of water clarity are somewhat greater in the spring than in the summer, especially for CB4 (Figs. 6 and 7). Generally, water quality improves in both spring and summer after the TN–TP trade over the allocation scenario in the upper Bay.

Issue Related to TSS Loads

The total suspended solid (TSS) loads to the Bay, and other physical conditions, used in the nine scenarios of this study are the same as the PR2000, and only the TN and TP loads vary. In water quality implementation practice, nitrogen and phosphorus reductions are usually accompanied by TSS reduction, especially in nonpoint source controls. In a separate study, 27 scenarios with variable TN, TP, and TSS loads, were run, and it was found that the shapes (or curvatures) of DO attainment curves versus TN and TP loads (e.g., the DO=5.4 mg/L curve in Fig. 2) are virtually

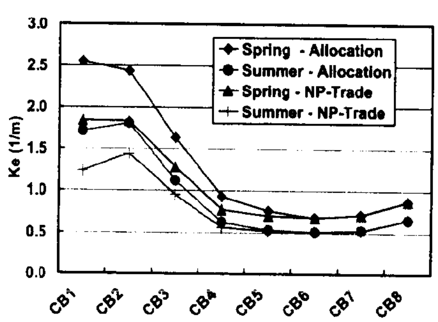

Fig. 7. Light extinction coefficient (K_e) in spring and summer for the allocation scenario and the NP-trade scenario

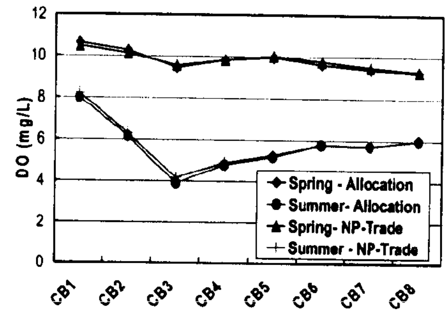

Fig. 8. Bottom DO concentration in spring and summer for the allocation scenario and the NP-trade scenario

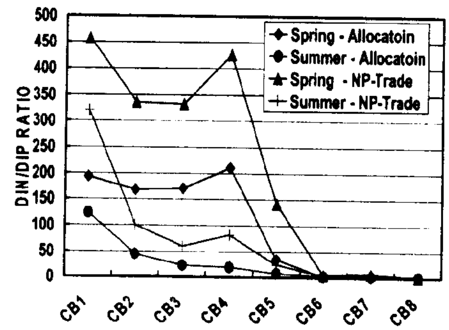

Fig. 9. DIN/DIP ratio in spring and summer for the allocation scenario and the NP-trade scenario

the same for the TSS load given by the PR2000 Scenario and for 80% of that amount. With more TSS reduction, the curve of DO=5.4 mg/L moves toward the point of TN and TP loads at 100% PR2000. This indicates that a greater TSS reduction would allow less nitrogen and phosphorus reductions to meet an equivalent DO water quality standard.

Conclusion

The continuous function of DO versus nitrogen and phosphorus loads from the response surface analysis provides trade-offs in total nitrogen and phosphorus load controls to achieve a specific DO requirement in the Chesapeake. The trade-off curves of total nitrogen and total phosphorus load provide information to explore flexible and/or cost-effective alternatives in nutrient reduction management. An effective trade-off is one that would generally intensify an existing predominant nitrogen or phosphorus limitation. Whether the water quality is improved or degraded is dependent on the extent of the trade and the nitrogen–phosphorus conditions in local areas, which may vary temporally or geographically. Trade-off that degrades water quality should be avoided. The acceptable TN–TP load trade-off is that alternative load control yielding a similar or better water quality condition, and this should be verified by model and monitoring data.

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